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**ONE-FIFTH-SCALE
AND ONE-HALF-SCALE
TWO-DIMENSIONAL SEISMIC TESTS**

by
D. PETERSON and B. E. OLSEN

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ONE-FIFTH-SCALE AND ONE-HALF-SCALE TWO-DIMENSIONAL SEISMIC TESTS

by
D. PETERSON and B. E. OLSEN

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ABSTRACT

Uni-axial seismic tests were performed on 1/5-scale and 1/2-scale two-dimensional models of the HTGR core consisting of 73 graphite elements in a hexagonal array. Core displacement and velocity, boundary support force, and in-core element force were measured. The test rigs were excited in two directions: across-the-flats of an element and across-the-corners. Results from the two models were compared on a normalized scale basis to check the scaling laws.

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1. SUMMARY AND CONCLUSIONS

Seismic tests were performed on 1/5-scale and 1/2-scale, two-dimensional HTGR core models. The core models consisted of 73 graphite elements in a hexagonal array contained in a test rig having adjustable boundaries to permit testing of a range of in-core gaps. The test rig was excited uniaxially in two separate directions: "across-flats" and "across-corners" of a fuel element. The excitation included both sinusoidal and time history earthquake type input. Measured parameters included element displacement and velocity, boundary support force, and in-core element forces.

This report contains complete records of the calibration, verification, testing, and data reduction phases of the two test programs, as well as data analysis and discussion of pertinent data. The bulk of the data are contained in Ref. 1.

The following is a summary of the more important test results and conclusions:

1. The two-dimensional partial core vibrates as a lumped mass when subjected to harmonic or near harmonic excitation input. Lumping varies with frequency and is a maximum (near 100%) at the frequency of maximum force. (See Section 4.4.2.3.)
2. Resonance diagrams indicate a single resonance from sinusoidal sweep tests at constant g-level. The resonance is typical of a nonlinear system and is characterized by a sudden jump in response dependent only on the core gap. The jump frequency decreases with an increase in core gap. The core structure exhibits a spring hardening effect. (See Sections 4.4.2.1 and 4.4.2.2.)

3. Maximum in-core or boundary support forces and maximum core velocity do not occur at the resonant frequency but at a lower frequency defined as the frequency of maximum force. The frequency of maximum force varies with core gap in the same manner as the jump frequency. (See Sections 4.4.2.1 and 4.4.2.2.)
4. The frequency response of the core across-corners is not significantly different from that across-flats. (See Section 4.4.2.2.)
5. The overall system damping in the two-dimensional array is very high (estimated at about 50% of critical). (See Section 5.4.2.3.)
6. The core response to the time history earthquake input shows maximum values at the boundary positions with decreasing magnitudes towards the center of the core. (See Section 4.4.3.1.)
7. Compared to the El Centro earthquake, the GA design earthquake No. 3 induces both higher relative velocities and forces. (See Section 4.4.3.1.)
8. Overall maximum velocities and forces generated by the earthquake input increase with core gap. However, a change in core gap that changes the core frequency response characteristics causes the maximum values to occur at different times (peaks) during the earthquake. (See Section 4.4.3.1.)
9. The in-core element forces, in particular the 1/2-scale forces, contain large random errors and are not considered useful data. (See Section 7.)

10. The $1/5$ - and $1/2$ -scale models are distorted with respect to each other. This is illustrated from normalized $1/5$ - and $1/2$ -scale plots of resonant frequencies and force data. (See Section 6.)

2. INTRODUCTION

The design of a reactor plant is complex, particularly in the seismic area where considerable efforts are expended to achieve a safe design consistent with NRC regulatory requirements.

Of considerable concern is the integrity of the reactor core and core support design when subjected to an earthquake. General Atomic has decided to determine the effects of seismic loading from analytical codes developed specially for the core structures. The capability of these codes must be proven, and so, to verify the codes, a program of scale model seismic tests has been undertaken. The tests reported on herein are part of this program.

These tests were performed on 1/5- and 1/2-scale core models consisting of 73 elements in a planar array. They had the following specific objectives:

1. To provide test data for correlation with analytical results from one- and two-dimensional models of the core for the purpose of code verification.
2. To ascertain the behavior of the core model in terms of resonant frequency, boundary force, and interelement velocities to changes in gap between fuel elements.
3. To obtain data for comparing identical 1/5- and 1/2-scale tests to aid in verifying the scaling laws assumed for the model designs.

These tests were subcontracted to outside vendors, the 1/5-scale test to Wyle Laboratories and the 1/2-scale test to Approved Engineering Test Laboratories (AETL), both Los Angeles-based companies. Their responsibilities included the tasks of testing and data acquisition only. Test design, data reduction, and analysis were performed by GA personnel.

3. TEST SCOPE

The tests were conducted on a planar array of 73 blocks shown schematically in Fig. 3-1. The input excitation was uniaxial and applied separately in two orthogonal directions: "across-flats" of a fuel block and "across-corners" of a fuel block. Since the rig was symmetrical, the across-corners input was actually applied at 30° to the primary across-flats direction. This simplified the testing and had no effect on the test results.

The input to the test rig in both axes was of three different types:

1. Sinusoidal sweep (SINS) at 0.5 decade/minute from 1.5 Hz up to 15 Hz and back down to 1.5 Hz. The test specifications for the 1/5-scale test had set the lower frequency limit at 0.5 Hz, but this had to be raised because of shaker limitations. Also because of this limitation, the input level was lowered to 0.75 g fixture acceleration.
2. Sinusoidal dwell (DWELL) at a selected frequency for a minimum of 10 cycles at steady state. The selected frequency was one of interest (usually near resonance) during the sine sweep. A DWELL was concluded by a near instantaneous (30 ms) shutdown of the excitation, which was to have provided damping information as the block motion died out. This technique was successful for the 1/2-scale test, but not for the earlier 1/5-scale test, where the technique used was not fast enough to provide an instantaneous shutdown. Therefore, at the conclusion of the regular testing, an additional scope of work was added to provide better damping data.

Fig. 3-1. Schematic of 73-element, two-dimensional section

3. Time history (TH) motion of a primarily narrowband random nature, as contained in an earthquake, amplified and filtered through the reactor building structures. The GA artificial design earthquake and the El Centro earthquake were employed; they are identified in the tests as earthquakes No. 3 and No. 9, respectively (Ref. 2). These earthquakes represent the floor response at the center of gravity of the core, and were generated for soft soil conditions (65,000 lb/in.) and 5% structural damping (Figs. 3-2 through 3-5). The peak acceleration input level to the test rig was 0.5 g equivalent ground acceleration, which corresponds approximately to 1.0 g fixture acceleration.

A complete summary of all tests performed is given in Tables 3-1 and 3-2. The two models were tested for several core gap values ranging from 0.05 to 0.4 in. for the 1/5-scale and 0.125 to 1.0 in. for the 1/2-scale. The in-core instrumentation was located at several positions, as shown in Fig. 3-6, which assured that a distribution of in-core response could be obtained.

Fig. 3-2. One-fifth-scale fixture response to GA design earthquake, soft soil, 5% damping, 0.5 g ground acceleration

Fig. 3-3. One-fifth-scale fixture response to El Centro earthquake, soft soil, 5% damping, 0.5 g ground acceleration

Fig. 3-4. One-half-scale fixture response to GA design earthquake, soft soil, 5% damping, 0.5 g ground acceleration

Fig. 3-5. One-half-scale fixture response to El Centro earthquake, soft soil, 5% damping, 0.5 g ground acceleration

TABLE 3-1
TEST SCOPE - 1/5-SCALE, TWO-DIMENSIONAL TESTS

Test No.	Tape No.	Test Type	Ground Acceleration ^(a) (g)	Frequency Range (Hz)	Inst. Block Loc. ^(b)	Total Core Gap (in.)
Across-Flats						
1	102	Sine sweep	0.75	2.2-15-2.2	1	0.05
		Sine sweep	0.75	2.2-15-2.2	1	0.10
	106	Sine dwell	1.0	14.0	1	0.10
		Time history	0.5	--	1	0.10
		Sine sweep	0.375	2.2-15-2.2	2	0.10
	107	Sine dwell	0.75	7.5	2	0.10
		Time history	0.5	--	2	0.10
2	108	Sine sweep	0.75	2.2-15-2.2	2	0.20
		Sine dwell	0.75	8.0	2	0.20
		Time history	0.5	--	2	0.20
		Sine sweep	0.75	2.2-15-2.2	1	0.20
	111	Sine dwell	0.75	8.0	1	0.20
		Time history	0.5	--	1	0.20
	113	Sine sweep	0.75	2.2-15-2.2	1	0.15
3	114	Sine sweep	0.75	2.2-15-2.2	1	0.25
		Sine sweep	0.75	2.2-15-2.2	1	0.30
	116	Sine dwell	0.75	7.0	1	0.30
		Time history	0.5	--	1	0.30
		Sine sweep	0.75	2.2-15-2.2	2	0.30
	117	Sine dwell	0.75	7.0	2	0.30
		Time history	0.5	--	2	0.30

TABLE 3-1 (Continued)

Test No.	Tape No.	Test Type	Ground Acceleration (a) (g)	Frequency Range (Hz)	Inst. Block Loc. (b)	Total Core Gap (in.)
Across-Flats						
4		Sine sweep	0.75	2.2-15-2.2	2	0.40
		Sine dwell	0.75	6.0	2	0.40
		Time history	0.5	--	2	0.40
		Sine sweep	0.75	2.2-15-2.2	1	0.40
	124	Sine dwell	0.75	6.0	1	0.40
		Time history	0.5	--	1	0.40
	125	Sine sweep	0.75	2.2-15-2.2	1	0.35
Across-Corners						
5		Sine sweep	0.75	2.2-15-2.2	3	0.10
	140	Sine dwell	1.0	13.0	3	0.10
		Time history	0.5	--	3	0.10
		Sine sweep	0.75	2.2-15-2.2	4	0.10
	127	Sine dwell	0.75	9.0	4	0.10
		Time history	0.5	--	4	0.10
6		Sine sweep	0.75	2.2-15-2.2	4	0.20
	128	Sine dwell	0.75	9.0	4	0.20
		Time history	0.5	--	4	0.20
		Sine sweep	0.75	2.2-15-2.2	3	0.20
	129	Sine dwell	0.75	4.0	3	0.20
		Time history	0.5	--	3	0.20
7		Sine sweep	0.75	2.2-15-2.2	3	0.30
	130	Sine dwell	0.75	7.0	3	0.30
		Time history	0.5	--	3	0.30
		Sine sweep	0.75	2.2-15-2.2	4	0.30
	131	Sine dwell	0.75	3.5	4	0.30
		Time history	0.5	--	4	0.30

TABLE 3-1 (Continued)

Test No.	Tape No.	Test Type	Ground Acceleration (a) (g)	Frequency Range (Hz)	Inst. Block Loc. (b)	Total Core Gap (in.)
Across-Corners						
8	132	Sine sweep	0.75	2.2-15-2.2	4	0.40
		Sine dwell	0.75	6.0	4	0.40
		Time history	0.5	--	4	0.40
	133	Sine sweep	0.75	2.2-15-2.2	3	0.40
		Sine dwell	0.75	3.0	3	0.40
		Time history	0.5	--	3	0.40

(a) Sine sweep and sine dwell acceleration refer to fixture level.

(b) See Fig. 3-2.

TABLE 3-2
TEST SCOPE - 1/2 SCALE, TWO-DIMENSIONAL TESTS

Test No.	Test Type	Ground ^(a) Acceleration (g)	Frequency Range (Hz)	Instrumented Element Location (b)	Total Core Gap (in.)
Across-Flats					
8	Sine sweep	0.75	1.5-15-1.5	1	0.125
7	Sine sweep	0.75	1.5-15-1.5	1	0.25
7	Sine dwell	0.75	TBD	1	0.25
7	Time history	0.75	--	1	0.25
9	Sine sweep	0.75	1.5-15-1.5	2	0.25
9	Sine dwell	0.75	TBD	2	0.25
9	Time history	0.75	--	2	0.25
10	Sine sweep	0.75	1.5-15-1.5	2	0.50
10	Sine dwell	0.75	TBD	2	0.50
10	Time history	0.75	--	2	0.50
5	Sine sweep	0.75	1.5-15-1.5	1	0.50
5	Sine dwell	0.75	TBD	1	0.50
5	Time history	0.75	--	1	0.50
6	Sine sweep	0.75	1.5-15-1.5	1	0.375
4	Sine sweep	0.75	1.5-15-1.5	4	0.625
3	Sine sweep	0.75	1.5-15-1.5	1	0.75
3	Sine dwell	0.75	TBD	1	0.75
3	Time history	0.75	--	1	0.75
11	Sine sweep	0.75	1.5-15-1.5	2	0.75
11	Sine dwell	0.75	TBD	2	0.75
11	Time history	0.75	--	2	0.75
2	Sine sweep	0.75	1.5-15-1.5	1	0.875
1	Sine sweep	0.75	1.5-15-1.5	1	1.00
1	Sine dwell	0.75	TBD	1	1.00
1	Time history	0.75	--	1	1.00

TABLE 3-2 (Continued)

Test No.	Test Type	Ground ^(a) Acceleration (g)	Frequency Range (Hz)	Instrumented Element Location ^(b)	Total Core Gap (in.)
12	Sine sweep	0.75	1.5-15-1.5	2	1.00
12	Sine dwell	0.75	TBD	2	1.00
12	Time history	0.75	--	2	1.00
Across-Corners					
13	Sine sweep	0.75	1.5-15-1.5	3	1.00
13	Sine dwell	0.75	TBD	3	1.00
13	Time history	0.75	--	3	1.00
20	Sine sweep	0.75	1.5-15-1.5	4	1.00
20	Sine dwell	0.75	TBD	4	1.00
20	Time history	0.75	--	4	1.00
19	Sine sweep	0.75	1.5-15-1.5	4	0.75
19	Sine dwell	0.75	TBD	4	0.75
19	Time history	0.75	--	4	0.75
14	Sine sweep	0.75	1.5-15-1.5	3	0.75
14	Sine dwell	0.75	TBD	3	0.75
14	Time history	0.75	--	3	0.75
15	Sine sweep	0.75	1.5-15-1.5	3	0.50
15	Sine dwell	0.75	TBD	3	0.50
15	Time history	0.75	--	3	0.50
18	Sine sweep	0.75	1.5-15-1.5	4	0.50
18	Sine dwell	0.75	TBD	4	0.50
18	Time history	0.75	--	4	0.50
17	Sine sweep	0.75	1.5-15-1.5	4	0.25
17	Sine dwell	0.75	TBD	4	0.25
17	Time history	0.75	--	4	0.25
16	Sine sweep	0.75	1.5-15-1.5	3	0.25
16	Sine dwell	0.75	TBD	3	0.25
16	Time history	0.75	--	3	0.25

(a) Sine sweep and sine dwell acceleration refer to fixture level.

(b) See Fig. 3-2.

- LEGEND**
- BOUNDARY FORCE
 - BOUNDARY VELOCITY
 - ▲ IN-CORE FORCE
 - | IN-CORE VELOCITY
 - 1 IN-CORE INSTRUMENT POSITION

Fig. 3-6. Layout of test instrumentation

4. ONE-FIFTH SCALE, TWO-DIMENSIONAL TEST

This section contains information pertaining only to the 1/5-scale, two-dimensional test. The equivalent information for the 1/2-scale test is found in Section 5. Comparisons between 1/5- and 1/2-scale test results are contained in Section 6.

All requirements for the test design, instrumentation, data acquisition, test plan, and accuracy of measurements are given in the 1/5-scale test specification (Ref. 2).

4.1. DESCRIPTION OF TEST APPARATUS

4.1.1. General

The test rig was designed to act as a rigid containment structure for a horizontal array of seventy-three 1/5-scale fuel blocks. The test rig and model core setup can be seen in Figs. 4-1 and 4-2. It was actuated by an electrohydraulic shaker, and was supported by hydraulic bearings. The test rig was hexagonal in shape and was provided with two attachment points for separate single-axis excitation in two directions: "across-flats" and "across-corners" of a fuel element.

4.1.2. Actuator

The actuator was a specially made hydrashaker, Wyle No. W-8000-4. The actuator was capable of providing 70,000 force-lb and a maximum stroke of 4 in. double amplitude. The shaker was limited to a maximum velocity of 22 in./s. This limitation was tied to the lack of pumping capacity, but given an infinite power source the only shaker limitations were the force and stroke already listed. However, a

Fig. 4-1. Test rig and core model

Fig. 4-2. Hydraulic bearings and actuator

practical limit of velocity was reached when fluid flow through the valve reached 200 gpm. At higher velocities, resistance of the valve consumed a greater portion of the input power.

The servo valve was the primary component of the actuator control system shown in Fig. 4-3. The input signal was an electrical signal corresponding to the desired actuator displacement. The input signal was achieved by an open-loop system, shown in Fig. 4-4, and the desired response was maintained by the closed-loop, displacement-feedback system. The frequency response of the control system was flat from dc to greater than 30 Hz, as was demonstrated by the Fixture Evaluation Test (See Section 4.3.)

4.1.3. Bearing System

The bearing system was composed of three Team hydrastatic bearings: two V-type bearings (No. 1830-V8-7) and a T-type bearing (No. 1830-T8-7). These three bearings were arranged in parallel, with the T-bearing in the center and the two V-bearings flanking it. The two V-bearings prevented lateral motion, and the T-bearing prevented vertical motion. The locations of these bearings are shown in drawings 74-E-33 and 74-D-45 of the Wyle drawing package summarized in Table 4-1.* A partial view of one of the V-bearings can be seen in the foreground of Fig. 4-2.

4.1.4. Test Rig

The test rig was a hexagonal aluminum structure mounted on the bearing system previously described. It is clearly pictured in Fig. 4-1, and its design details are shown in the drawings listed in Table 4-1. The design objective for the rig was to provide a rigid boundary with individually adjustable sides so that the load could be measured at each boundary block. The purpose of the rigidity was to assure that all motion was purely a

* All drawings referenced in this report are General Atomic proprietary information.

1/5 SCALE 2D TEST

Fig. 4-3. Test excitation control system

TIME HISTORY:

SINE SWEEP:

Fig. 4-4. Input to actuator

TABLE 4-1
SUMMARY OF 1/5-SCALE TEST DRAWINGS^(a)

Wyle Drawing Number	GA Foreign Print Number	Title
Layout	487791-2	GA 1/5-Scale-Model Seismic Test Layout
53766-74-C-20	487791-3	GA 1/5-Scale-Model Seismic Test Upper Insert
53766-74-C-22	487791-4	GA 1/5-Scale-Model Seismic Test Lower Insert
53766-74-C-23	487791-5	GA 1/5-Scale-Model Seismic Test Standoff
53766-74-C-24	487791-6	GA 1/5-Scale-Model Seismic Test Reaction Plate
53766-74-C-25	487791-7	GA 1/5-Scale-Model Seismic Test Boundary Plate
53766-74-C-26	487791-8	GA 1/5-Scale-Model Seismic Test Boundary Plate
53766-74-C-27	487791-9	GA 1/5-Scale-Model Seismic Test Boundary Stud
53766-74-C-29	487791-10	GA 1/5-Scale-Model Seismic Test Fixture Assy (Sheet 1)
53766-74-E-29	487791-11	GA 1/5-Scale-Model Seismic Test Fixture Assy (Sheet 2)
53766-74-D-30	487791-12	GA 1/5-Scale-Model Seismic Test Fuel Element
53766-74-C-31	487791-13	GA 1/5-Scale-Model Seismic Test Tee Bar
53766-74-C-32	487791-14	GA 1/5-Scale-Model Seismic Test Precision Nut
53766-74-E-33	487791-15	GA 1/5-Scale-Model Seismic Test Setup Assy
53766-74-D-34	487791-16	GA 1/5-Scale-Model Seismic Test LVDT Mount
53766-74-D-45	487791-20	GA 1/5-Scale-Model Seismic Test Fixture Assy (Bottom View)

(a)
These drawings are General Atomic Company proprietary information.

function of the block stiffness and not of the test rig stiffness. The loads were measured at discrete boundary points, rather than obtaining one value for a whole side, since it was possible to obtain identical data from the analytical models. The test rig boundaries were designed to be perfectly perpendicular to the test rig floor so that no vertically misaligned core element impacts could occur. An analysis showed that 0.1° of misalignment was permissible without altering the collision behavior of the blocks. Hence, this value represented a design criterion for the test rig. The behavior of the section model, therefore, was analogous to one where the core column effects have been eliminated.

4.1.5. Core Model

The test rig served as a container for the core model. The core model consisted of seventy-three 1/5-scale model graphite fuel blocks, of which 70 were of the configuration shown in drawing 74-D-30. The remaining three blocks were instrumented blocks shown schematically in Fig. 4-5. These instrumented blocks were moved from location to location to provide data on the distribution of the loads within the core.

The 1/5-scale block was a scaled version of the prototype HTGR fuel element. Prior to the core design, a scaling analysis was performed to arrive at a set of scaling laws, which are given in Table 4-2. The dimensional analysis and assumptions made are discussed in Ref. 4. The scale factor λ is a constant, and for the 1/5-scale test model, $\lambda = 1/5$.

Exact similitude in the 1/5-scale block design was not achieved due to (1) the practical difficulty and cost of attempting to simulate 208 prototype fuel and gas cooling holes in a 1/5-scale block and (2) the selection of graphite as the structural material. The 1/5-scale graphite blocks were designed with a one-hole or multi-hole (instrumented blocks) pattern made to match the scaled mass and coefficient of restitution. It was determined that obtaining the correct scaled down factors for these two

Fig. 4-5. One-fifth-scale test in-core instrumentation

TABLE 4-2
SCALING LAWS FOR TEST MODEL

Length	$X_m = \lambda X_p$
Velocity	$\dot{X}_m = \sqrt{\lambda} \dot{X}_p$
Acceleration	$\ddot{X}_m = \ddot{X}_p$
Time	$t_m = \sqrt{\lambda} t_p$
Force	$F_m = \lambda^3 \left(\frac{\rho_m}{\rho_p} \right) F_p$
Stiffness	$K_m = \lambda^2 \left(\frac{\rho_m}{\rho_p} \right) K_p$
Modulus ^(a) of elasticity	$E_m = \lambda \left(\frac{\rho_m}{\rho_p} \right) E_p$
Coefficient of restitution	$e_m = e_p$
Coefficient of friction	$\mu_m = \mu_p$

where λ = scale factor
 m = model
 p = prototype HTGR

(a) Related to across-the-flats stiffness of a block.

parameters would have the least distortion effect on the dynamic characteristics of the core model. This, however, results in a 1/5-scale block that is too stiff and tends to produce dynamic loads that are too large on a true scale basis.

4.1.6. Standoffs

Each block of the core model was supported by three standoffs made out of steel. The three standoffs fixed each core block in a plane, and the four-bar-linkage nature of the block motion maintained parallelism between the blocks and the test rig floor. In addition, the standoffs were toleranced such that no block-to-block impact could occur with a vertical misalignment of greater than 0.1° , the maximum value for simulated flat-to-flat impacts. Drawings of the standoffs and inserts are listed in Table 4-1.

4.2. INSTRUMENTATION

The instrumentation used for this test was rig control instrumentation, boundary instrumentation, in-core instrumentation, and data acquisition instrumentation. All instrumentation, with the exception of the boundary load cell transducers, had been used previously during the 1/5-scale full-array test (Ref. 5) and verification was therefore unnecessary. A summary of instrumentation is listed in Table 4-3, and each type is described separately below.

4.2.1. Test Rig Control

The rig motion transducers consisted of an LVDT used for positional feedback for the control system and an accelerometer that recorded rig acceleration. This accelerometer was not used as part of the control system.

TABLE 4-3
INSTRUMENTATION LIST - 1/5-SCALE, TWO-DIMENSIONAL TEST

Instrument	Manufacturer	Model No.	Range	ID No.	Accuracy ^(a) (%)
Load cell	Kistler	903A	0-24,000 lb	W45510	1.0
Load cell	Kistler	903A	0-24,000 lb	W45511	1.0
Load cell	Kistler	903A	0-24,000 lb	W45512	1.0
Load cell	Kistler	903A	0-24,000 lb	W45513	1.0
Load cell	Kistler	903A	0-24,000 lb	W45514	1.0
Accelerometer	Endevco	2264-4500	0-4,500 g	W45206	0.5
Accelerometer	Endevco	2264-4500	0-4,500 g	W45207	0.5
Accelerometer	Endevco	2264-4500	0-4,500 g	W45205	0.5
Accelerometer	Endevco	2262-25	0-25 g	W45283	0.5
Strain gage	J. P. Semicon.	080-50	0-5,000 μ in./in.	W45272	1.0
LVDT	Collins	SS707	± 3 in.	W45284	0.5
LVDT	Collins	SS706	± 1 in.	W45202	0.5
Displ. gage	Dees	524-W	0-0.150 in.	W45274	N/A
Displ. gage	Dees	524-W	0-0.150 in.	W45275	N/A
Signal cond.	Endevco	4470	N/A	S/N CB21	N/A
Signal cond.	Endevco	4470	N/A	S/N CB20	N/A
Signal cond.	Endevco	4470	N/A	CB19	N/A
Signal cond.	Endevco	4470	N/A	AK79	N/A
Signal cond.	Endevco	4470	N/A	AK78	N/A
Signal cond.	Endevco	4470	N/A	BB96	N/A

TABLE 4-3 (Continued)

Instrument	Manufacturer	Model No.	Range	ID No.	Accuracy (%)
Charge amplifier	Endevco	4477.2	1-3-10-30-100-300	45515	1.0
Charge amplifier	Endevco	4477.2	1-3-10-30-100-300	45516	1.0
Charge amplifier	Endevco	4477.2	1-3-10-30-100-300	45517	1.0
Charge amplifier	Endevco	4477.2	1-3-10-30-100-300	45518	1.0
Charge amplifier	Endevco	4477.2	1-3-10-30-100-300	45519	1.0
Amp. bridge Cond.	Endevco	4476.2A	1-3-10-30-100-300	45509	0.5
VBR amplifier	Endevco	4640	X100	ZA28	1.0
VBR amplifier	Endevco	4640	X50	ZA14	1.0
Computer	Varian	620/F100	N/A		0.3
Oscillograph	Honeywell	1012	36 channel	30413	2.0 Time 5.0 Paper
Power supply	Dressen Barnes	27144	0-15 Vdc	98059	0.5
Power supply	Kepco	SM160-2	0-160 Vdc	95178	0.5
Oscilloscope	Tektronix	535A	95029 V/cm 0.1 sec -5 sec	6002	3.0
VTVM	B&K	2416	0-1,000 Vac	30815	5.0
Oscillator	Kroan-Hite	440A	0.001 Hz to 10 kHz	30689	1
Digital multimeter	Electro-Inst.	630	100 mV to 750 Vdc	1539	0.3
Peak holder	Wyle	73-C-54	0-5 Vdc	None	5.0
Peak holder	Wyle	73-C-54	0-5 Vdc	None	5.0
Peak Holder	Wyle	73-C-54	0-5 Vdc	None	5.0

TABLE 4-3 (Continued)

Instrument	Manufacturer	Model No.	Range	ID No.	Accuracy (%)
Peak holder	Wyle	73-C-54	0-5 Vdc	None	5.0
Peak holder	Wyle	73-C-54	0-5 Vdc	None	5.0
Peak holder	Wyle	73-C-54	0-5 Vdc	None	5.0
Peak holder	Wyle	73-C-54	0-5 Vdc	None	5.0
Peak holder	Wyle	73-C-54	0-5 Vdc	None	5.0
Peak holder	Wyle	73-C-54	0-5 Vdc	None	5.0
Digital multimeter	Fluke	8000A	0-1200 Vac	30207	0.5
Oscillator	Hewlett-Packard	200 CDR	5 Hz to 600 kHz	30819	2.0
VBR amplifier	Endevco	4640 M3	X100	AA47	1.0
VBR amplifier	Endevco	4640 M3	X100	AA48	1.0

(a) Random instrument error.

Since the control system was adequate to control the piston at the two extremes - bare head (no load) and with a 50,000 lb specimen - it should have been adequate to easily control the two-dimensional 3000 lb specimen. However, the control system had been tuned to account for an oil-column resonance phenomenon present when used with the full-array specimen, and it was feared that this tuning might interfere with the control when used with the smaller specimen. Therefore, a fixture evaluation test was performed. (See Section 4.3.1.)

The rig accelerometer was located on the rig base, adjacent to the stinger attachment point.

The fixture LVDT was mounted to the rig base on the side opposite the stinger. This installation is shown in the lower right corner of Fig. 4-1.

4.2.2. Boundary Instrumentation

The boundary instrumentation was of two types: (1) load cell assemblies to measure impact force, and (2) an LVDT to measure block displacement relative to the support boundary.

The load cell assemblies were each comprised of two Kistler 903A quartz load washers mounted in parallel (lower right of Fig. 4-6). This configuration allowed accurate load measurement for all types of core element collisions (i.e., edge and flat collisions). The load cell assemblies were carefully designed to assure accurate load measurement of the high frequency (1000 Hz) block impacts that could occur.

The load cell assemblies were located at five selected positions on the boundary.

The boundary LVDT (DX003) was a Collins Model SS706 located on the support boundary and extending to contact block No. 3 (Fig. 4-6). The

Fig. 4-6. Boundary support instrumentation

preload spring provided with the LVDT was too stiff and would have restricted motion, so it was removed. The LVDT tip was instead glued to the block with a GE silicon adhesive, which provided a permanent bond yet allowed a limited amount of rotation. For across-corners testing, since the block motion was at an angle to the allowable LVDT travel, the LVDT installation was modified to a pivoted arrangement which allowed free movement of the block.

The purpose of the LVDT, in addition to providing information on the displacement of the core relative to the boundary, was to provide relative velocity measurements. This was accomplished by differentiating the displacement signal. The displacement information was used in calculating core damping data. See Section 4.4.2.4.

4.2.3. In-Core Instrumentation

The in-core instrumentation consisted of strain gages, accelerometers, displacement transducers, and contact gages contained in three adjacent fuel blocks. This scheme is illustrated in Figs. 4-5 and 4-7. By relocating this system of blocks in the core, the distribution of response throughout the core was obtained.

The strain gages were semiconductor type, installed in a seven-hole block as shown in the figures. They were located in such a position as to receive maximum strain from a compressive load on one face (Ref. 5). There was some doubt as to whether the calibration technique was adequate, and additional calibration was performed which uncovered an impact calibration technique for impact loads (Ref. 6). In addition, the block loads were verified by running a sine sweep with the strain-gaged block located adjacent to a boundary load cell assembly. Good correlation between the block loads and support boundary loads was achieved. However, from measurements in the center of the core it was still not obvious that the calibrations were entirely adequate since there was evidence of block

Fig. 4-7. One-fifth-scale test in-core instrumentation

collisions on several of the hexagonal sides. On the boundary, the block was primarily hit on one side. The strain-gage loads representing in-core data are therefore only considered approximate.

The accelerometer was an Endevco Model 2269 piezoresistive instrument with a dynamic range of ± 4500 g. One was located in each of the three instrumented blocks as shown in Fig. 4-7. It was intended to measure bulk block acceleration, but these low-level accelerations were masked by the accelerations caused by block impact. The acceleration loads measured by this instrument were only a function of the filtering selected, and thus the readings from this instrument were of little use.

Dees capacitive-type displacement transducers were located as shown in Fig. 4-7. Their purpose was to determine the maximum separation of the fuel blocks during test. In addition, the displacement output from the Dees gages was digitized at a sufficient rate to allow the displacement trace to be differentiated to determine the relative velocity between blocks. The Dees gages were calibrated at the start of testing, but because of their temperature sensitivity they were checked at regular intervals during testing.

4.2.4. Data Acquisition Instrumentation

This consisted of signal conditioning and amplification of the basic transducer signals as well as digitization and recording of the digitized data onto magnetic tape. Schematics of the signal conditioning and amplification stage for the various instruments are shown in Figs. 4-8 through 4-12. The digitization and recording stages were accomplished by a Varian 620/F100 data acquisition computer incorporating a multiplexer unit.

The standard digitization rate was 0.005 s for all the instruments. However, some data (load cells and strain gages) required better definition since the duration of the response peak might be shorter than the standard

Fig. 4-8. Typical load cell block diagram

Fig. 4-9. Typical linear displacement transducer (LVDT) block diagram

Fig. 4-10. Typical strain gage block diagram

Fig. 4-11. Typical accelerometer block diagram

Fig. 4-12. Typical capacitive type displacement transducer (Dees) block diagram

time interval, in which case the peak would not be recorded. In such a case, a smaller digitization rate was chosen (one-half, one-quarter, etc., of the standard rate) or a peak holder unit incorporated. The peak holder recorded and held the maximum value during the standard 0.005-s interval before it was picked up by the computer at the end of that interval. The instrument then reset itself. Smaller digitization rates and peak holders were employed at the same time throughout the testing. Since smaller digitization rates increase the number of instrument channels, which was limited by the computer capacity, peak holders were preferred. However, peak holders cannot be used when it is necessary to accurately correlate the maximum peak value in time.

4.3. SYSTEM VERIFICATION

4.3.1. Fixture Evaluation

An evaluation of fixture dynamic rigidity and control system adequacy was performed to assure that an observed vibration mode could not be attributed to either a fixture or control system resonance. The evaluation consisted of a fixture transmissibility test and a "ring" test. The fixture transmissibility test consisted of a sine sweep throughout the frequency range of interest (0 to 30 Hz), in which no resonance was observed. A complete description of the transmissibility test may be found in the final test report (Ref. 7). A "ring" test, consisting of impacting the test fixture with a hammer and observing the natural frequency oscillations, followed. The lowest natural frequency was thereby seen to be 250 Hz, which is far above the frequency range of interest.

4.3.2. "Standoff" Friction

The "standoff" support was designed so it would not affect the block motion; it required a coefficient of friction less than 0.04. This capability was demonstrated at the block nominal position and at full deflection. Checking was done by pushing on a fuel block with a calibrated spring scale. The maximum static friction was found to be approximately half the required value.

4.3.3. Boundary Support Load Cell Verification

A new boundary load cell design to measure support loads was adopted for this test, which is described in Section 4.2.2. A procedure was written for the verification test (Ref. 8), and a task description is in the final test report (Ref. 7). The test results of the verification test are given in Ref. 9, which showed the load cell assembly capable of reproducing block impact loads and contact duration with $\pm 5\%$ accuracy.

4.3.4. System Calibration

The system calibration, accomplished in accordance with Appendix 2 of the Wyle test procedure (Ref. 10), consisted of an end-to-end (transducer-to-computer) instrument channel identification and calibration. All dc devices (all displacement gages) were calibrated by moving the device a measured amount and recording the resulting computer counts. All ac devices (accelerometers and load cells) were calibrated by inserting a simulated transducer signal of known voltage amplitude provided by an oscillator. The binary devices (contactors) were calibrated by checking the make-and-break and make-and-hold function of each. Complete documentation and results of the system calibration may be found in Ref. 11.

4.3.5. Verification Test

To verify all aspects of the test system, and to assure compatibility between the contractor data acquisition hardware and GA data reduction software, a verification test was performed at maximum gap. A description of the verification test and the problems encountered may be found in Ref. 7. The results are documented in Ref. 12.

4.4. TEST RESULTS

4.4.1. General

The results presented in this section represent typical response selected from the bulk of the test data. A complete set of the reduced

data is collected in Ref. 1, and a summary list of this data is given in Table 4-4.

The test results exist in three basic forms: (1) the original digital data tapes stored in the GA computer archives and data packages, including analog data on oscillograph paper, in Record Storage (Sorrento Valley) as required for system verification, (2) all the initial data reduction listings (computer printouts) resulting from runs that used the software outlined in Ref. 12, also found in Record Storage, and (3) hand and computer plots contained in Ref. 1. A detailed description of the data reduction procedure and the codes involved are given in Ref. 13.

4.4.2. Core Dynamic Characteristics

The data analysis performed to determine the dynamic characteristics of the 1/5-scale, two-dimensional core was based on excitation input in the form of sinusoidal sweeps and dwells as described in Section 3.

In the data reduction process, PEAK and PEAKAVG amplitude values were employed to obtain plots of frequency response, phase angle, and lumping parameters (Ref. 12). The definitions of these terms are given in Fig. 4-13. The PEAK values were used to establish absolute maximum and total range of examined parameters. The PEAKAVG represented a mean value of all peaks in a frequency interval of 0.2 Hz. This process tended to reduce the effects on the response from such factors as system randomness and misaligned element impacts, and provided smoother and more legible plots to analyze.

The phase angle between response and input was employed in establishing a resonant condition. The definition of phase is shown in Fig. 4-14. It is seen that the peak value of the response is related to the maximum amplitude value of the input where the peak response coincides with the core impacting the support boundary. However, as for linear systems, the resonant condition is established by obtaining a 90° phase shift between response and input.

TABLE 4-4
SUMMARY OF 1/5-SCALE TEST DATA CONTAINED IN REF. 1

Data Type	Response	Excitation Input	Excitation Direction	Instrument Position	Gap (in.)	Section
Frequency response curves (peak average)	Force Velocity Phase angle	SINS	Across-flats	CP1	0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40	1.1
Maximum (peak average) response versus gap	Force Velocity	SINS	Across-flats	CP1 CP2	--	1.2
Maximum (peak average) response near resonance versus gap	Force Velocity	SINS	Across-flats	CP1 CP2	--	1.3
Maximum (peak average) response distribution	Force Velocity	SINS	Across-flats	CP1 CP2	0.10 0.20 0.30 0.40	1.4
Maximum (peak average) response distribution near resonance	Force Velocity	SINS	Across-flats	CP1 CP2	0.10 0.20 0.30 0.40	1.5
Maximum response distribution	Force Velocity	TH GA No. 3 El Centro	Across-flats	CP1 CP2	0.10 0.20 0.30 0.40	1.6
Maximum response versus gap	Force	TH GA No. 3 El Centro	Across-flats	CP1 CP2	--	1.7
Maximum response versus gap	Force	TH GA No. 3 El Centro	Across-corners	CP3 CP4	--	1.8

$$\text{PEAK} = \text{MAX} (P_i)$$

P_i = AMPLITUDE OF PEAK i

$$\text{PEAKAVG} = \frac{\sum_i P_i}{N}$$

N = NUMBER OF PEAKS CONSIDERED

Fig. 4-13. Illustration of PEAK and PEAKAVG

Fig. 4-14. Illustration of PHASE

A core lumping factor was defined to determine the compaction geometry of the core which would aid in the interpretive analysis of the core motion characteristics and the resonance phenomenon, etc. Core lumping is related to the accumulative core gap as follows (Fig. 4-15),

$$L = \frac{g_1 + g_{10}}{\sum_{i=1}^{10} g_i}$$

where g_1 and g_{10} are the gaps measured between the boundary and the outermost core element (Fig. 3-6) and

$$\sum_{i=1}^{10} g_i$$

is the total across-core gap between boundaries. Therefore $L = 100\%$ means zero gap between core elements and represents maximum core mass density or lumping.

4.4.2.1. Resonance Phenomena. A typical resonance curve for the 1/5-scale core obtained from a sinusoidal sweep-up at constant acceleration of 0.75 g is shown in Fig. 4-16. The curve is characteristic of the behavior of a non-linear and discontinuous structure such as the core section tested. At a certain frequency, depending on the cumulative core gap, a sudden drop-off in response occurs. This is clearly illustrated in the figure and is commonly referred to as the jump phenomenon. For excitation across-flats and a 0.2 in. core gap, the jump is recorded at a frequency of 10.0 Hz as shown.

In the frequency sweep-down (Fig. 4-17) the response jumps from low to a large but noticeably lower frequency than during sweep-up. This shows that the system has a region of instability in the frequency range between the jumps where the response amplitude is indeterminate.

CORE LUMPING PARAMETER,

$$\mathcal{L} = \frac{g_1 + g_{10}}{\sum_{i=1}^{10} g_i}$$

Fig. 4-15. Definition of core lumping

Fig. 4-16. Frequency response curve (peak average force), 0.2 in. gap, across-flats, sweep-up

Fig. 4-17. Frequency response curve (peak average force), 0.2 in. gap, across-flats, sweep-down

The fact that the sweep-down frequency is lower than the sweep-up frequency indicates that the system exhibits a spring hardening effect, which means that the jump frequency will increase with an increase in excitation g-level. The frequency dependence on input amplitude, however, was not established since testing was confined to one g-level only.

The jump phenomenon occurs at core resonance as shown in Fig. 4-18 where the phase angle between load response and input displacement is plotted. The curve indicates a 90° phase shift between response and input at approximately 10.0 Hz.

A further indication of the resonance condition is obtained from Fig. 4-19, which represents the relative velocity of a core element as a function of frequency. It is seen that the maximum occurs near the 10.0 Hz jump frequency.

Maximum in-core or boundary support forces, however, do not occur at the resonant frequency. All the instruments show the maximum occurs at a lower frequency than the jump frequency. For a 0.2 in. core gap, the frequency of maximum force occurs at approximately 5.4 Hz, as shown in Figs. 4-16 and 4-17. This frequency also coincides with the overall maximum core velocity (relative to the boundary) as shown in Fig. 4-20, which may be attributed to a higher percentage of core lumping at this frequency. This is further discussed in Section 4.4.2.3.

4.4.2.2. Frequency Response. Both the jump frequency and frequency of maximum response were found to be dependent on the core gap. This is shown in Figs. 4-16 and 4-21 where the resonance curves for 0.2 in. and 0.4 in. gaps can be compared.

The variation of resonant frequency with core gap is shown in Fig. 4-22. It is seen that both the jump frequency and the frequency of maximum force decrease as the core gap increases. All instrument records analyzed indicated a jump frequency for the same gap within 0.25 Hz. The frequency of maximum force, however, shows more scatter. The maximum deviation from the mean is represented in the figure.

Fig. 4-18. Phase shift between load response and input

Fig. 4-19. Frequency response curve (peak average element velocity), 0.2 in. gap, across-flats

Fig. 4-20. Frequency response curve (peak average core velocity), 0.2 in. gap, across-flats

Fig. 4-21. Frequency response curve (peak average force), 0.4 in. gap, across-flats

Fig. 4-22. Core frequency response as a function of gap

Figures 4-23 and 4-24 represent typical resonance curves for tests conducted in the direction across-corners of an element (see Fig. 3-1). From the analysis of the data, it was found that the frequency response of the 1/5-scale core across-corners was not significantly different compared to that obtained from the across-flats direction.

4.4.2.3. Mode Shapes. Due to the nonlinearities of the core structure, the mode shapes of vibration are not readily described as for linear systems. However, the core structure exhibited distinct motion characteristics with respect to core lumping, relative velocities, and distribution of force throughout the structure; these are described at the core jump frequency and the frequency of maximum force.

For harmonic input motion, provided the input amplitude is larger than the core gap, the core moves as a lumped mass. The percentage of lumping, as defined in Fig. 4-15, varies both with the position of the core relative to the boundary and with the frequency of excitation. During a cycle of oscillation, maximum lumping occurs shortly after the core boundary impact force has peaked out. This is shown in Fig. 4-25 where close to 100% lumping is achieved.

By representing the maximum lumping during one cycle as a function of frequency (Fig. 4-26), it is observed that the core motion is higher lumped at the frequency of maximum force than at the jump frequency. This probably explains why the forces are not a maximum at resonance.

The maximum boundary support forces and in-core forces are shown plotted in Fig. 4-27. This figure represents the distribution of "peak average" forces as opposed to "peak" forces, which are shown for comparison in Fig. 4-28. The "peak" values are about 30% higher. The distributions show that the forces are maximum at the boundary and decrease towards the center of the core. Also, the forces vary with core gap as shown in Fig. 4-29. As expected, the forces increase with larger gaps. The same trends are observed for the forces plotted at the jump frequency (Fig. 4-30), but they are smaller in magnitude as commented on earlier.

Fig. 4-23. Frequency response curve (peak average force), 0.2 in. gap, across-corners

Fig. 4-24. Frequency response curve (peak average velocity), 0.4 in. gap, across-corners

Fig. 4-25. Core lumping

Fig. 4-26. Core lumping as a function of frequency

1/5 SCALE 2D TEST

● LOCATION OF
MEASURED FORCE

ACROSS-FLATS
SWEEP-UP
0.75 g FIXTURE ACCEL.
GAP = 0.2 IN.

Fig. 4-27. Maximum (peak average) force distribution, 0.2 in. gap, across-flats

LOAD CELL ASSEMBLY

ACROSS-FLATS
SWEEP-UP
0.75 g FIXTURE ACCELERATION
GAP = 0.2 IN.

Fig. 4-28. Maximum (peak) force distribution, 0.2 in. gap, across-flats

Fig. 4-29. Maximum (peak average) force distributions, across-flats

Fig. 4-30. Maximum (peak average) force distributions at jump frequency, across-flats

The maximum relative block velocities at the frequency of maximum force are shown in Fig. 4-31. It is seen that the average maximum velocity occurs between the two outermost elements and at about twice the relative velocity between the core and the support boundary. This makes sense since the outermost block will travel a short distance (gap between the two outermost blocks) in the opposite direction to the rest of the core after impact with the boundary. It will then hit the incoming core with a velocity nearly equal to that of the general core velocity. The core and the relative block velocities also increase with an increase in core gap as shown in Fig. 4-32. The same trends are observed for the velocities plotted at the jump frequency, as shown in Fig. 4-33.

4.4.2.4. Core Damping. Core damping causes energy losses in the core primarily due to impact and friction between elements. It is difficult if not impossible to obtain quantitative data for these effects. Therefore, an attempt was made to obtain a value for the overall effect in terms of an equivalent viscous damping factor. This can be achieved by exciting the core with a sinusoidal dwell function and suddenly arresting the rig motion. The resulting core decay response in free vibration then provides a measure of equivalent viscous damping in the core.

The decay can either be correlated with analytical code predictions, from which the damping factor can be obtained, or by measuring the logarithmic decay directly from the test data. If at least two cycles of oscillation take place, an estimate of viscous damping factors may be made from the following expression:

$$\xi = \frac{1}{2\pi n} \ln \frac{X_n}{X_0} \quad ,$$

where X_0 = the first amplitude,

X_n = the n^{th} amplitude,

n = number of cycles between X_0 and X_n .

1/5 SCALE 2D TEST

▲ IN-CORE AND
BOUNDARY FORCE (LB_f)

ACROSS-FLATS
SWEEP-UP
0.75 g FIXTURE ACCELERATIO
GAP = 0.2 IN.

Fig. 4-31. Maximum (peak average) relative velocity distribution at frequency of maximum force, 0.2 in. gap, across-flats

Fig. 4-32. Maximum (peak average) relative velocity distribution at frequency of maximum force, across-flats

Fig. 4-33. Maximum (peak average) relative velocity distribution near jump frequency, across-flats

Calculation of a viscous damping factor was not attempted, however, for the 1/5-scale test core because the rate at which the rig motion was terminated was less than the rate required for accurate damping calculations. Instead, damping calculations were performed for the 1/2-scale core with which satisfactory tests were carried out.

4.4.3. Time History Response

This section deals with the core response to time history excitation represented by the GA artificial design earthquake (shock 3) and the El Centro earthquake (shock 9) as described in Section 3.

The time history data reduction was performed with two data reduction programs to obtain peak values (THPEAK) (Ref. 13). The THPEAK routine prints the maximum peak value of each instrument reading during the entire earthquake. For the El Centro earthquake, however, caution should be exercised in the analysis of the reduced data. At the conclusion of the earthquake, a shutdown transient caused by numerical errors exists which for some gaps results in an overall maximum response. This false maximum should be ignored.

Time history peak values were also determined manually from Visicorder output. The instruments from which this output was available were CS-037, CS-065, LC-002, LC-072, and LC-073.

4.4.3.1. Velocities and Forces. Maximum values of relative velocities and forces in-core and at the support boundary resulting from the GA design earthquake and the El Centro earthquake are given in Figs. 4-34 through 4-43. These values represent the overall maximum for the indicated locations regardless of the time at which the maximum occurred.

Consistent with the response from the sinusoidal sweep tests, the distribution of in-core velocities shown in Fig. 4-34 indicates larger relative velocities between elements near the core boundary. The boundary support and in-core forces are shown in Fig. 4-35. Some scatter exists in

the boundary force readings, but opposite load cells (LC-072 and LC-002) should not necessarily read the same value since the input is not harmonic.

A comparison between the responses generated by the GA design earthquake and the El Centro earthquake, taken from Figs. 4-34 through 4-37, shows that the GA design earthquake induced both higher relative velocities and forces.

The maximum relative velocities and forces are shown as a function of core gap in Figs. 4-38 and 4-39. Generally, it is seen that the maximums increase as the core gap increases. However, a change in gap tends to change the frequency response characteristics of the core; consequently, the maximum may occur at different times (peaks) during the earthquake. This is demonstrated in Figs. 4-41 and 4-42. These figures show the response occurring at major peaks in the earthquake designated by numbers 1 through 5 as defined in Fig. 4-40. Depending on the core gap value, either of the peaks may cause the overall maximum response. For this reason, the curves in Figs. 4-38 and 4-39 will exhibit considerable deviation from the trends established by the sine sweep data.

Figure 4-43 gives the distribution of forces for the GA design earthquake applied in the across-corners direction (30° to the across-flats direction).

Fig. 4-34. Maximum relative velocity distribution, GA design earthquake, 0.2 in. gap, across-flats

Fig. 4-35. Maximum force distribution, GA design earthquake, 0.2 in. gap, across-flats

1/5 SCALE 2D TEST

LOAD CELL
ASSEMBLY

■ BOUNDARY
VELOCITY (IN./SEC)

▲ IN-CORE
VELOCITY (IN./SEC)

EL CENTRO
ACROSS-FLATS
0.5 g GROUND ACCELERATION
GAP = 0.2 IN

Fig. 4-36. Maximum relative velocity distribution, El Centro, 0.2 in. gap, across-flats

1/5 SCALE 2D TEST

● IN-CORE AND
BOUNDARY FORCE (LB)

EL CENTRO
ACROSS-FLATS
0.5 g GROUND ACCELERATION
GAP = 0.2 IN.

Fig. 4-37. Maximum force distribution, El Centro, 0.2 in. gap, across-flats

Fig. 4-38. Maximum relative velocity distribution, GA design earthquake, across-flats

Fig. 4-39. Maximum force distribution, GA design earthquake, across-flats

Fig. 4-40. Identification of peaks causing high response, GA design earthquake

Fig. 4-41. Peak boundary support force variation with gap, GA design earthquake

Fig. 4-42. Peak in-core force variation with gap, GA design earthquake

1/5 SCALE 2D TEST

LOAD CELL
ASSEMBLY

● IN-CORE AND
BOUNDARY FORCE (LB)

GA DESIGN EARTHQUAKE 3
ACROSS-CORNERS
0.5 g GROUND ACCELERATION
GAP = 0.2 IN.

Fig. 4-43. Maximum force distribution, GA design earthquake, 0.2 in. gap, across-corners

5. ONE-HALF SCALE, TWO-DIMENSIONAL TEST

This section contains information pertaining only to the 1/2 scale test. Comparisons between the 1/5- and 1/2-scale test results are presented in Section 6.

All requirements for test design, instrumentation, data acquisition, test plan, and accuracy of measurement are given in the 1/2-scale test specification (Ref. 14). A list of the drawings used is given in Table 5-1.

Test response phenomena in the 1/2-scale tests that are similar to those in the 1/5-scale tests are not always described or discussed in this section. Cross references have instead been made to the 1/5-scale test, where appropriate, to avoid duplication.

5.1. DESCRIPTION OF TEST APPARATUS

5.1.1. General

The 1/2-scale test rig is very similar to the 1/5-scale rig in construction as shown in Fig. 5-1. With respect to the core model, emphasis was put on producing a design that produced compatibility with the 1/5-scale dynamic characteristics.

5.1.2. Actuator

The rig was driven by a 10,000 force-pound Shore-Western hydraulic actuator. The maximum double amplitude for this system was 9.0 in. The actuator was controlled by a double closed-loop system with both a control acceleration feedback loop and a control displacement feedback loop (Fig. 5-2). The command signal to the servo-amplifier was not open-loop as in

TABLE 5-1
SUMMARY OF 1/2-SCALE TEST DRAWINGS^(a)

AETL Drawing Number	GA Foreign Print Number	Title
5430-5486-03	487792-004	Frame
5430-5486-04	487792-005	Boundary Support
5430-5486-05	487792-006	Core Floor Support
5430-5486-06	487792-007	Drive Adapter
5430-5486-07	487792-008	Core Floor Support (Sh 1)
	487792-008	Core Floor Support (Sh 2)
5430-5486-09	487792-009	Schedule
5430-5486-10	487792-010	Boundary Support - Detail
5430-5486-11	487792-011	Boundary Support - Detail
5430-5486-12	487792-012	Boundary Support - Detail
5430-5486-13	487792-013	Standoff
5430-5486-14	487792-014	Lower Insert
5430-5486-15	487792-015	Upper Insert
5430-5486-16	487792-016	Boundary Support - Detail
5430-5486-17	487792-017	Load Cell Calibration System
5430-5486-22	487792-018	Boundary Support - Nut
	010750B ^(b)	Fuel Element, Half-Size Model

^(a) These drawings are General Atomic Company proprietary information.

^(b) GA drawing

Fig. 5-1. One-half-scale test rig and core model

Fig. 5-2. Test excitation control system

the 1/5-scale test. Instead, a servo-monitor continually compared oscillator output with the output of the fixture accelerometer in order to maintain the required g-level. Subsequently, the displacement loop continually compared actual fixture displacement with the command signal and corrected for any possible error.

As in the 1/5-scale, two-dimensional test, the fixture evaluation indicated that the frequency response of the control system was flat from dc to 30 Hz. A further discussion of the fixture evaluation is presented in Section 5.3.

5.1.3. Bearing System

The AETL bearing system was the result of an extensive modification of the original design due to an unsatisfactory fixture evaluation. Apparently the original system, which utilized four rows of Thompson "roundway bearings," did not add the necessary rigidity to the core floor support plate. The new system consisted of 16 Thompson "super ball bushings," which guided the rig along four 2-in.-diameter parallel shafts as shown in AETL Drawing 5430-5486-05A. The bearing system was conservatively designed for supporting the core floor support plate, which was made of aluminum to keep the weight down. Maximum allowable vertical load for these bearings was $16 \times 3000 \text{ lb} = 48,000 \text{ lb}$, while the fixture/core assembly had a gross weight of less than 5000 lb.

5.1.4. Test Rig

The 1/2-scale test rig (Fig. 5-1) was very similar to the 1/5-scale rig. The design details are shown in the drawings listed in Table 5-1. The rig provided "rigid" boundary supports, which could be individually adjusted, and three stand-offs for individual support of each core block. The 1/2-scale rig employed the same design criteria as the 1/5-scale rig.

5.1.5. Core Model

As in the 1/5-scale, two-dimensional test, the core model consisted of 73 fuel blocks. The design details of the 1/2-scale blocks are illustrated in GA drawing 010750B. The 1/2-scale block was a scaled prototype HTGR fuel element, as was the 1/5-scale block, but all elements were designed with a seven-hole pattern. Seventy of the blocks included additional weights located symmetrically in six of the seven holes to achieve the correct scaled weight of 32.4 lb (AETL drawing 5430-5486-24). The other three blocks were instrumented blocks that had three symmetrically located weights in holes where no in-core instrumentation existed.

5.2. INSTRUMENTATION

The 1/2-scale test instrumentation consisted of rig control, boundary and in-core transducers, and data acquisition instrumentation. A summary of all instrumentation is listed in Table 5-2; each type and its calibration are described below.

5.2.1. Test Rig Control

Fixture instrumentation consisted of a strain gage accelerometer mounted on the test rig and a Collins LVDT mounted on the actuator. These instruments monitored the response for control and verification of the rig input as shown schematically in Fig. 5-2. The calibration of both transducers is given in the test procedure (Ref. 15).

The control system performed according to specified criteria in all respects except during Test No. 8, for the smallest core gap of 0.125 in. At this gap setting, automatic control could not be maintained near 15 Hz. Subsequently, manual control was used, but the control g-level, 0.75 g, could still not be maintained within the specified error margin of 10%. However, extensive testing was not required at this gap and a modification to the control system was not performed.

TABLE 5-2
TEST INSTRUMENTATION - 1/2-SCALE, TWO-DIMENSIONAL TEST

Instrument	Manufacturer	Model	Range	ID No.	Accuracy
Digital multimeter	Fluke	8120A	10 mV to 1000 V	E1032V	0.3%
Tape recorder	Ampex Corp.	CAT No. 150000		E1059V	N/A
RMS voltmeter	Ballantine Labs.	3200/6	0 to 320 V	E1048V	±2%
Ampl. servo/monitor	Spectral Dynamics	SD105A	1,10,100,1000 g	D214L	±4%
Accelerometer	Endevco	2213	0-1000 g	D152L	±2%
Carrier amplifier	Electrodynamics Corp.	1-11313	40 mA into 26 ohms	E258L	±1%
Carrier amplifier	Electrodynamics Corp.	1-11313	40 mA into 26 ohms	E262L	±1%
Tape recorder	Precision Instruments	P1-214		E112L	N/A
Linear motion transducer	G. L. Collins Corp.	SS-208	0 to ±4.0 in.	D817V	
LVDT	G. L. Collins Corp.	LMT-719T31	±5 in.	D818V	0.3%/100°F
X-Y plotter	F. L. Moseley	135	0 to 50 V	D731V	0.2%
X-Y plotter	F. L. Moseley	135A-02	0 to 50 V	D748V	0.2%
Sweep oscillator	Spectral Dynamics	SD104A-5	0.005 Hz to 50 kHz	D752V	±1%
Log voltmeter/converter	Hewlett-Packard	7562A	100 V to 100 V	D763V	±0.25 /dB
Bandpass filter	Spectral Dynamics	SD100AR-2A	2 Hz	D883V	N/A
Load washer	Kistler	9031	13,000 lb	D884V	±1%
Load washer	Kistler	9031	13,000 lb	D885V	±1%
Load washer	Kistler	9031	13,000 lb	D886V	±1%
Load washer	Kistler	9031	13,000 lb	D887V	±1%
Load washer	Kistler	9031	13,000 lb	D888V	±1%
Computer	Varian	620/L-100	16 bit, 8 k core	D802V	N/A
Magnetic tape system	PICO Peripheral Interface	MT-62	9 track, 800 bpi	D803V	N/A
Tape recorder	Wangco	10	45 ips, 800 bpi	D804V	N/A
Power supply		620/L-100	±5, ±12 Vdc	D805V	±5%
Power supply		03-950085-01	±5, ±15, ±24 Vdc	D806V	
Teletype	Teletype Corp./Varian	33T4	10 cps	D808V	N/A
Peakholder	Sine Engineering	05-10344	0.5 to 10 V	D809V	5%
Peakholder	Sine Engineering	05-10344	0.5 to 10 V	D810V	5%
Peakholder	Sine Engineering	05-10344	0.5 to 10 V	D811V	5%
Peakholder	Sine Engineering	05-10344	0.5 to 10 V	D812V	5%
Peakholder	Sine Engineering	05-10344	0.5 to 10 V	D813V	5%
Peakholder	Sine Engineering	05-10344	0.5 to 10 V	D814V	5%
Peakholder	Sine Engineering	05-10344	0.5 to 10 V	D815V	5%
Load washer	Sine Engineering	902A	0.5 to 10 V	D820V	±1%
Load washer	Kistler	902A	8000 lb	D821V	±1%
Load washer	Kistler	902A	8000 lb	D822V	±1%
Load washer	Kistler	902A	8000 lb	D823V	±1%
Load washer	Kistler	902A	8000 lb	D824V	±1%
Load washer	Kistler	902A	8000 lb	D825V	±1%
Load washer	Kistler	902A	8000 lb	D826V	±1%
Load washer	Kistler	902A	8000 lb	D827V	±1%
Load washer	Kistler	902A	8000 lb	D828V	±1%
Load washer	Kistler	902A	8000 lb	D829V	±1%
Load washer	Kistler	902A	8000 lb	D830V	±1%
Load washer	Kistler	902A	8000 lb	D831V	±1%

TABLE 5-2 (Continued)

Instrument	Manufacturer	Model	Range	ID No.	Accuracy
Load washer	Kistler	902A	8000 lb	D832V	±1%
Load washer	Kistler	902A	8000 lb	D833V	±1%
Load washer	Kistler	902A	8000 lb	D834V	±1%
Load washer	Kistler	903A	13,000 lb	D835V	±1%
Load washer	Kistler	903A	13,000 lb	D836V	±1%
Load washer	Kistler	903A	13,000 lb	D837V	±1%
Load washer	Kistler	903A	13,000 lb	D838V	±1%
Load washer	Kistler	903A	13,000 lb	D839V	±1%
Load washer	Kistler	903A	13,000 lb	D840V	±1%
Load washer	Kistler	903A	13,000 lb	D841V	±1%
Load washer	Kistler	903A	13,000 lb	D842V	±1%
Load washer	Kistler	903A	13,000 lb	D843V	±1%
Load washer	Kistler	903A	13,000 lb	D844V	±1%
Bridge balance	Sine Engineering	05-10341	6 to 15 V	D845V	0.5%
Bridge balance	Sine Engineering	05-10341	6 to 15 V	D846V	0.5%
Bridge balance	Sine Engineering	05-10341	6 to 15 V	D847V	0.5%
Bridge balance	Sine Engineering	05-10341	6 to 15 V	D848V	0.5%
Bridge balance	Sine Engineering	05-10341	6 to 15 V	D849V	0.5%
Bridge balance	Sine Engineering	05-10341	6 to 15 V	D850V	0.5%
Bridge balance	Sine Engineering	05-10341	6 to 15 V	D851V	0.5%
Bridge balance	Sine Engineering	05-10342	6 to 12 V	D852V	2%
Buffer amplifier	Sine Engineering	05-10346	0 to 10 V	D853V	±0.5%
Buffer amplifier	Sine Engineering	05-10346	0 to 10 V	D854V	±0.5%
Buffer/supply	Sine Engineering	05-10347	0 to 15 V	D855V	0.5%
Buffer/supply	Sine Engineering	05-10347	0 to 15 V	D856V	0.5%
Buffer/supply	Sine Engineering	05-10347	0 to 15 V	D857V	0.5%
Buffer/supply	Sine Engineering	05-10347	0 to 15 V	D858V	0.5%
Dual filter	Sine Engineering	05-10348	DC to 800 Hz	D859V	1%
Dual filter	Sine Engineering	05-10348	DC to 800 Hz	D860V	1%
Dual filter	Sine Engineering	05-10348	DC to 800 Hz	D861V	1%
Dual filter	Sine Engineering	05-10348	DC to 800 Hz	D862V	1%
Charge amplifier	Sine Engineering	05-10345	X10 to X110	D863V	1%
Charge amplifier	Sine Engineering	05-10345	X10 to X110	D864V	1%
Charge amplifier	Sine Engineering	05-10345	X10 to X110	D865V	1%
Charge amplifier	Sine Engineering	05-10345	X10 to X110	D866V	1%
Charge amplifier	Sine Engineering	05-10345	X10 to X110	D867V	1%
Charge amplifier	Sine Engineering	05-10345	X10 to X110	D868V	1%
Charge amplifier	Sine Engineering	05-10345	X10 to X110	D869V	1%
Summing amplifier	Sine Engineering	05-10343	±10 V	D876V	1%
Summing amplifier	Sine Engineering	05-10343	±10 V	D877V	1%
Summing amplifier	Sine Engineering	05-10343	±10 V	D878V	1%
Summing amplifier	Sine Engineering	05-10343	±10 V	D879V	1%
Summing amplifier	Sine Engineering	05-10343	±10 V	D880V	1%
Summing amplifier	Sine Engineering	05-10343	±10 V	D881V	1%
Summing amplifier	Sine Engineering	05-10343	±10 V	D882V	1%

5.2.2. Boundary

Boundary instrumentation consisted of load cells and a displacement transducer. Boundary support loads were measured by load cell assemblies at five boundary supports in the same positions as for the 1/5-scale test as shown in Fig. 3-6. Each assembly consisted of five Kistler load washers arranged symmetrically between two aluminum plates. There was one load cell at each corner of these plates and a fifth at the center. The assembly was rigidly fixed in a plane parallel to a boundary core block face, and the outputs of all five load cells were electronically summed to represent the total support load. Verification of the boundary load cell assembly to measure impact loads within 15% of the actual loads is documented in Ref. 16. The method of verification involved vertical drops of a known mass with an accelerometer attached to the support assembly. In the worst case, a load cell reading deviated from the accelerometer reading by 11.4%. Furthermore, drops made for a number of impact orientations, including edge and corner impacts, did not change the accuracy of the measurements.

The second boundary instrument was a LVDT, which measured relative displacement between a boundary support and a fuel element. These displacement readings were later converted into relative velocity by the data reduction software. Calibration of the LVDT consisted of actual measurements of various extensions of the instrument along with the corresponding output voltages and computer readouts.

Test rig control instrumentation also included provisions for a sudden arrest of the test rig motion at maximum shaker displacement. This capability was designed to facilitate core structural decay in free vibration from which damping measurements could be obtained. The circuitry is included in Fig. 5-2. Test rig arrest was accomplished by transferring the sinusoidal command signal to a dc command signal of equal peak level. The control system was built to perform the rig arrest within 0.1 cycle of the sinusoidal dwell, which at 5 Hz typically means within 20 ms.

5.2.3. In-Core Instrumentation

The in-core instrumentation consisted of an accelerometer, eddy current displacement probes, strain gages, and contact gages all attached to three adjacent fuel blocks (Fig. 5-3). The three instrumented blocks were moved to four core positions to provide a distribution of in-core data as for the 1/5-scale test (Fig. 3-6).

In the 1/2-scale, two-dimensional test, the accelerometer served as a monitor of block acceleration and for possible use in correlation with the contactors to determine block impact time. The AETL test procedure (Ref. 16) describes the calibration of the in-core accelerometer.

Two eddy current probes measured relative displacement between adjacent core blocks. These probes also provided in-core relative velocity in a manner similar to that of the boundary LVDT. Eddy current probes, which work by magnetic induction, were substituted for the capacitance gages (Dees) employed in the 1/5-scale test because of their superior sensitivity and linearity characteristics, as well as being easier to calibrate. Calibrations were performed between each core position change in order to eliminate minor drift problems. The drift was thought to be generated by deposits of graphite dust on the probe tip during testing, or possible movement of the probe relative to its graphite bed.

In the 1/5-scale test, one strain gage only was used to measure block loads. However, the load effects from collisions on hexagonal faces in off-axis directions were not accounted for. Although a single strain gage can be calibrated to measure force from collisions on all faces, it is doubtful whether the off-axis face can be positively identified. Hence, for the 1/2-scale tests, an attempt to use three strain gages to resolve the collision forces on the three front faces (1, 2, and 6) was made, as shown in Fig. 5-4. The strain gages were calibrated from drop tests with a 34 lb weight, which impacted the instrumented block vertically (Refs. 17

Fig. 5-3. In-core block instrumentation (core position No. 1)

Fig. 5-4. One-half-scale element strain gage calibration

and 18). The weight produced flat-on hits on the three front faces and force/strain factors were calculated for each impact orientation. These factors were assembled in a matrix and utilized in an analysis to determine force vectors on the three faces.

Eight contactors consisting of thin copper foil were installed on the center block of the three in-core instrumentation blocks (Fig. 5-3). These were located in the four corners of the block face such that impact orientation could be recorded. Each contactor subjected to data acquisition logic had three modes of operation: open, closed, and change (open to close, close to open, etc.).

During the test runs, three of the eight contactors were malfunctioning in the second (closed) mode. This was attributed to a slight (1 to 2 mils) recession of the contactors in their respective graphite beds during pretest preparations. Therefore, the data on impact orientation was not accurate.

5.2.4. Data Acquisition Instrumentation

Data acquisition hardware preceding the computer consisted of a variety of analog signal conditioners, including charge amplifiers for the boundary load cells, bridge balances and summers for the strain gages, peak holders for both load cells and strain gages, and buffer amplifier/supplies for the displacement transducers. This instrumentation, which was similar to that in the 1/5-scale test, is described in the AETL test procedure (Ref. 15). After signal conditioning, the computer digitized the data at the digitization rates listed in the reference. The Varian 620 computer incorporated a multiplexer unit, an analog/digital converter, and a buffered input/output. It provided output to a teletype as well as magnetic tape. The digital tape was copied by AETL before submittal of each data package. The FM (analog) tapes, which were recorded simultaneously, were stored at the test laboratory for future examination and possible redigitization of specific channels.

5.3. SYSTEM VERIFICATION

5.3.1. Fixture Evaluation

The purpose of the fixture evaluation was two-fold. Primarily, the evaluation measured test rig transmissibility (the core model at zero gap setting) in order to verify that no rig resonances existed in the frequency range from 1.5 to 30 Hz. In addition, the reaction mass acceleration loads were measured to assure that the entire motion was transmitted to the test rig and core model. Acceptable transmissibility in this frequency range was a value less than 1.5, transmissibility being the ratio of response acceleration to control acceleration.

The response acceleration was measured in the direction of rig motion at the top of the boundary support farthest from the actuator, the location at which transmissibility would be at its greatest. Several other locations were also monitored to check the possibility of local resonances. Reference 19 describes the fixture evaluation in detail.

The initial fixture evaluation indicated that the original bearing design was inadequate. The accepted evaluation after extensive bearing modification produced a fixture resonance that peaked above 30 Hz. The transmissibility ratio at 30 Hz was 1.5. This is acceptable since the actual test frequency range is below 15 Hz.

5.3.2. Instrument Signal Verification

The data acquisition system recorded 80 channels of instrumentation on magnetic tape in both digital and analog form. On-line printout of one record of taped response selected near core resonance was examined after each test for basic verification of transducer signals.

In addition, preliminary verification was made from oscillograph plots of six channels of instrumentation, which were plotted for the full test duration. Input excitation of the test rig was continually monitored and Verified by fixture LVDT output on the Visicorder, on an X-Y plotter during time history runs, and by fixture acceleration output on another X-Y plotter during sine sweep runs.

5.3.3. System Calibration

Data acquisition at AETL included the capability of master insert calibration or individual insert calibrations of separate transducers. Master calibration, as described in detail in Ref. 15, involved inserting +5 Vdc into all signal conditioners, which then output a known number of computer counts in the calibrated mode. Any significant deviation from the expected values meant a malfunction between the transducer (excluding the transducer itself) and the computer. Such a sample was taken before and after each test. Actual transducer malfunctions were monitored even more frequently by pretest and post-test "tares." In addition, the dump of one complete record consisting of 24 scans (0.005 s each real time) of the 80 channels was made at the end of each test run.

5.3.4. System Pretest

A final verification (end-to-end) that the entire system functioned properly was performed. Here, an actual test run was made consisting of a sine sweep, sine dwell, and the two time histories at the maximum gap setting of 1.00 in. Subsequently, the digital data tape was reduced at GA.

Pretest data reduction indicated that the sinusoidal input to the test rig, as well as the quick shutdown procedure used following the sine dwell, satisfied the test specifications. Difficulties appeared in the time history input where the GA design earthquake was run with half of the required time base. Also, one of the peaks occurring in this earthquake was not at the specified magnitude. These anomalies were corrected.

The most significant result of the pretest was the fact that the in-core strain gages did not function correctly. Theoretically the concept of employing strain gages for obtaining fuel block loads is a logical method. However, a number of practical considerations made it inadequate. The main reason was perhaps the calibration mode, which strictly assumed a flat-on impact. A true flat-on impact rarely occurs in the core test and since block strains are very sensitive to the distribution of load, the calibration tends to become inaccurate. The strain gage application itself can also be questioned. In order to pick up a strain wave from an impact, the gage must have a large sensitivity, which necessitates a small gage length. Thus errors from nonflat impacts are magnified to a large extent.

As this method was found inadequate, an alternative load cell design with load washers was conceived which proved in later tests to give reliable results. However, for these 1/2-scale tests, accurate fuel block load data were not obtained.

5.4. TEST RESULTS

5.4.1. General

The data presented in this section is compatible with the data presented for the 1/5-scale tests, and represent typical response. The in-core strain gages calibrated to measure block loads, however, did not produce reliable data as discussed above. Although the response magnitudes are inaccurate, the data are still useful in the data analysis since the frequency response is not affected. A complete set of reduced data is collected in Ref. 1, and a summary of this data is given in Table 5-3.

The same data reduction procedures and codes used for the 1/5-scale test were employed for the 1/2-scale test.

TABLE 5-3
SUMMARY OF 1/2-SCALE TEST DATA CONTAINED IN REF. 1

Data Type	Response	Excitation Input	Excitation Direction	Instrument Position	Gap (in.)	Section
Frequency response curves (peak)	Velocity Force	SINS	Across-flats	CP1	1.00 0.875 0.75 0.675 0.50 0.375 0.25 0.125	2.1
Frequency response curves (peak)	Velocity Force	SINS	Across-flats	CP2	0.25 0.50 0.75 1.00	2.2
Frequency response curves (peak)	Velocity Force	SINS	Across-corners	CP3	1.00 0.75 0.50 0.25	2.3
Frequency response curves (peak)	Velocity Force	SINS	Across-corners	CP4	0.25 0.50 0.75 1.00	2.4
Maximum (peak) response vs. gap	Force Velocity	SINS	Across-flats	CP1 CP2	--	2.5
Maximum (peak) response near resonance vs. gap	Force Velocity	SINS	Across-flats	CP1 CP2	--	2.6
Maximum (peak) response distribution	Force Velocity	SINS	Across-flats	CP1 CP2	0.25 0.50 0.75 1.00	2.7
Maximum (peak) response distribution near resonance	Force Velocity	SINS	Across-flats	CP1 CP2	0.25 0.50 0.75 1.00	2.8
Maximum response distribution	Force Velocity	TH GA No. 3 El Centro	Across-flats	CP1 CP2	0.25 0.50 0.75 1.00	2.9

5.4.2. Core Dynamic Characteristics

Sinusoidal sweep and dwells were employed to determine the dynamic characteristics as described in Section 3.

In the data reduction process, only PEAK amplitude values were employed to obtain frequency response curves. The PEAK routine produces amplitude values somewhat higher than the PEAKAVG routine. As for the 1/5-scale test, these values were less than 30% higher. The PEAK and PEAKAVG routines are described in Section 4.4.2.

5.4.2.1. Resonance Phenomena. The 1/2-scale test core generally exhibited the same resonance characteristics as the 1/5-scale core as can be seen from the frequency response curves of force, velocity, and phase shown in Figs. 5-5 through 5-9. These characteristics are discussed in Section 4.4.2.1.

The 1/2-scale response showed the frequency of maximum force to be less pronounced than in the 1/5-scale test, and there was a slight change in the core velocity profile. This was probably due to core lumping, which had a somewhat different distribution with respect to frequency compared to the 1/5-scale core.

5.4.2.2. Frequency Response. The 1/2-scale core also showed a strong frequency dependence on core gap (Figs. 5-10 and 5-11): both the jump frequency (resonance) and the frequency of maximum force. The core frequency characteristics in the direction across-corners (Figs. 5-12 and 5-13) did not differ significantly from the across-flats direction, which was consistent with the 1/5-scale test results.

5.4.2.3. Mode Shapes. The overall 1/2-scale core motion characteristics were similar to the 1/5-scale characteristics described in Section 4.4.2.3. The maximum core lumping (Fig. 5-14), however, was relatively higher at resonance, which indicates that the 1/2-scale core was probably a more stable scale model design. It caused the force level at resonance to be close to the maximum forces.

Fig. 5-5. Frequency response curve (peak force), 0.5 in. gap, across-flats, sweep-up

Fig. 5-6. Frequency response curve (peak force), 0.5 in. gap, across-flats

Fig. 5-7. Phase shift between load response and input

Fig. 5-8. Frequency response curve (peak element velocity), 0.5 in. gap, across-flats

Fig. 5-9. Frequency response curve (peak core velocity), 0.5 in. gap, across-flats

Fig. 5-10. Frequency response curve (peak force), 1.0 in. gap, across-flats

Fig. 5-11. Frequency response as a function of gap

Fig. 5-12. Frequency response curve (peak force), 0.5 in. gap, across-corners

Fig. 5-13. Frequency response curve (peak element velocity), 1.0 in. gap, across-corners

Fig. 5-14. Core lumping as a function of frequency

Maximum boundary forces and in-core element relative velocities for a 0.5 in. core gap are plotted in Fig. 5-15. These are represented as "peak" values, defined in Section 4.4.2. The boundary forces at the frequency of maximum force and at resonance as a function of core gap are shown in Figs. 5-16 and 5-17. The corresponding in-core velocities are shown in Figs. 5-18 and 5-19. Both forces and velocities are shown to increase with an increase in core gap. All trends were similar to those in the 1/5-scale tests.

5.4.2.4. Core Damping. An attempt to obtain core damping data as discussed in Section 4.4.2.4 was made by exciting the core with sinusoidal dwell input and suddenly arresting the rig motion. The resulting core response in free vibration decay is shown in Fig. 5-20. By observing the impact force readings from the boundary load cells located at diagonally opposite positions, it is seen that the core comes to rest after less than one cycle of free vibration.

An effort was made to determine the equivalent viscous damping from the traces by correlating the core motion with that of a single-degree-of-freedom core model consisting of a mass, spring, and dashpot. From the analysis of several decay tests, it was determined that the core exhibited overall damping factors in the range of 30% to 50% of critical. It was not determined how damping was dependent on frequency or excitation g-level.

5.4.3. Time History Response

This section discusses the core response to time history excitation represented by the GA design earthquake No. 3 and the El Centro earthquake as described in Section 3. The data reduction methods are described in Section 4.4.3.

5.4.3.1. Velocities and Forces. Overall maximum boundary forces and in-core relative velocities for a 0.5 in. core gap are represented in Figs.

Fig. 5-15. Maximum (peak) force and element velocity distribution for 0.5 in. gap, across-flats

Fig. 5-16. Maximum boundary (peak) forces as a function of gap

Fig. 5-17. Maximum (peak) force as a function of gap near jump frequency

Fig. 5-18. Maximum (peak) relative velocity distribution at frequency of maximum force

Fig. 5-19. Relative (peak) velocity distributions near jump frequency

Fig. 5-20. Free vibration decay of core after sudden arrest

5-21 and 5-22. The distribution of velocities and forces are similar to 1/5-scale results discussed in Section 4.4.3.1. Again, the GA design earthquake is shown to generally induce a larger response compared to the El Centro earthquake.

A general increase in maximum velocity and force values is shown to occur as the core gap increases (Figs. 5-23 and 5-24). The influence of the core gap on the core frequency response characteristics and hence the response magnitudes is discussed using the 1/5-scale results. The 1/2-scale tests showed similar results.

Figure 5-25 shows the distribution of in-core relative velocities and boundary forces for the GA design earthquake applied in the across-corners direction.

1/2 SCALE 2D TEST

Fig. 5-21. Maximum force and relative velocity distribution for GA design earthquake, 0.5 in. gap, across-flats

1/2 SCALE 2D TEST

Fig. 5-22. Maximum force and relative velocity distribution for El Centro earthquake, 0.5 in. gap, across-flats

Fig. 5-23. Maximum relative velocity distribution for GA design earthquake, across-flats

Fig. 5-24. Maximum boundary forces for GA design earthquake as a function of gap

1/2 SCALE 2D TEST

LOAD CELL
ASSEMBLY

Fig. 5-25. Maximum force and relative velocity distribution for GA design earthquake, 0.2 in. gap, across-corners

6. COMPARISON BETWEEN 1/5-SCALE and 1/2-SCALE TESTS

The purpose of testing two models was to provide data for code correlation on two scales to gain greater confidence in the analytical methods used to predict prototype HTGR response.

The scale relationships to the prototype, given in Table 4-2, did not always hold true, as discussed in Section 4.1.5, since both models were distorted. This, however, is of little consequence to the verification of analytical methods unless all the response parameters are affected by the distortions and the overall model behavior does not remotely resemble that of the prototype.

The main distortion resulted from using graphite as a core element material. The use of graphite is not permitted if the model tests are to be performed in the same gravitational field as the prototype since the design condition,

$$\rho_m g_m l_m / E_m = \rho_p g_p l_p / E_p ,$$

becomes invalid.

The fact that g is constant and l fixed leaves p/E to be changed. Using graphite, however, produces a distortion in this quantity that affects the element contact (impact) time since the stress wave propagation is dependent on the material properties. This may have some influence on the other response parameters such as overall core behavior (displacement, lumping), frequency, velocity, and force.

The 1/5- and 1/2-scale models were, therefore, distorted also with respect to each other. However, by comparing the normalized model responses, it can be determined how important these distortions are and hence the usefulness of the models.

The model response parameters were compared over a range of core gaps by normalizing the 1/2-scale response to 1/5 scale and placing the 1/2- and 1/5-scale results on the same plot.

Clearly, the overall motion characteristics of the 1/5- and 1/2-scale cores were the same as concluded from the earlier discussion of results. The cores moved primarily as a lumped mass if the excitation displacement (double amplitude) was less than the core gap. Thus, the distortion in the element impact time did not influence the overall motion. This was probably due to the fact that the impact time (order of 0.1 ms) was very small compared to the block travel times between impacts (order of 0.1 s).

The normalized core resonant frequencies for 1/5 and 1/2 scale (Fig. 6-1) showed reasonable agreement (within 15%) in the gap range tested. This meant that the core frequency response was virtually independent of the element properties and primarily a function of the core gap. The influence of the boundary stiffness, if any, was eliminated by making this parameter "infinitely" stiff compared to the core structural stiffness.

The relative core element velocities normalized to 1/5 scale were compared at resonance for sinusoidal excitation (sweep-up) and at maximum force for the GA design earthquake (Figs. 6-2 and 6-3). Both comparisons showed the normalized 1/5- and 1/2-scale values to agree closely. Hence the velocities were also shown to be practically independent of element property.

We also know from simple element impact tests that the velocities were strongly dependent on the element damping properties and hence the coefficient of restitution. The restitution parameter, however, was modeled accurately according to the scaling laws and consequently did not contribute to distorting the velocities.

Fig. 6-1. One-fifth- and 1/2-scale comparisons - core frequency response

Fig. 6-2. One-fifth- and 1/2-scale comparisons - boundary force and element velocity at resonance

Fig. 6-3. One-fifth- and 1/2-scale comparisons - maximum element velocity response from GA design earthquake

The agreement between normalized 1/5- and 1/2-scale impact forces, on the other hand, was poor, as is shown in Figs. 6-2 and 6-4. Obviously, since this parameter was directly a function of contact time the distortion here tended to affect the forces. The 1/5-scale forces were consistently higher since ρ/E stayed constant going from 1/2 to 1/5 scale. For correct modeling, this quantity should have been larger for 1/5 scale according to the scaling laws. This made the 1/5-scale element stiffer or the contact time smaller relative to the normalized 1/2-scale value.

In conclusion, these comparisons show that ignoring the scaling of the ρ/E quantity will only affect the force response significantly.

Fig. 6-4. One-fifth- and 1/2-scale comparisons - maximum boundary force response from GA design earthquake

7. TEST DATA ERROR ANALYSIS

An estimate of errors in the 1/5- and 1/2-scale tests was performed in order to obtain the expected accuracy of the presented data. This is particularly important where the data is used for correlation with results from analysis and in the determination of correlation criteria.

In general, the test data contained both random and systematic errors. If data from repeated tests are available in a reasonable size sample, statistical analysis of the measurements can be employed to estimate the total random error involved. If repeated tests are not available, the random errors in the test system components must be obtained separately and compounded to obtain the total (random) error in the data measurements. Systematic errors, on the other hand, which tend to have the same algebraic sign, are not amenable to statistical treatment. In most instances, however, they are easily obtained from the raw data plots. The data reduction codes can assess this error and automatically adjust the data point. If not, the systematic error is added algebraically to the random error to obtain the overall total error.

From the test procedures, it was observed that only boundary support force test data were repeated once. The latter method of compounding test system component errors was therefore employed to evaluate the errors in the 1/5- and 1/2-scale tests.

7.1. ERROR SOURCES

The commonly known sources of error in these tests are as follows:

1. Test rig control
2. Test rig configuration and initial conditions
3. Core element properties

4. Data acquisition system
5. Instrument calibration or verification
6. Extraneous errors

7.1.1. Test Rig Control Error

These errors represent inaccuracies in the input excitation amplitude, waveform, and frequency as measured by the test rig LVDT.

There is a maximum permitted input amplitude and waveform error equal to $\pm 10\%$ in the test specification. Although the quality control procedures assured that this amount would not be exceeded, an error analysis was nevertheless performed to determine the actual errors.

Four tests using the 1/5-scale model and four using the 1/2-scale model were selected arbitrarily to assess the amplitude error. The test rig LVDT maximum double amplitude reading was recorded from Visicorder traces. Exact static LVDT calibration on the Visicorder eliminated the instrument error. The LVDT readings were then compared with the reference input as shown in Table 7-1. This table shows an average systematic error for the two earthquake inputs (shock 3 and shock 9) of +3.3% for the 1/5-scale test and +6.5% for the 1/2-scale test, which means that the magnitude of the input consistently was somewhat higher than the reference in both tests. The random error, which is represented by the fractional standard deviation (1σ) with respect to the mean LVDT reading, is 1.4% for the 1/5-scale and 2.4% for the 1/2-scale test.

These errors may not seem very large and might not influence the maximum response values to a large degree. Coupled with the waveform error, however, the random deviations in the input tend to cause small variations in the motion of the individual core elements, which is easily achieved since in the two-dimensional tests the elements are virtually

TABLE 7-1
ONE-FIFTH AND ONE-HALF SCALE TEST INPUT ERRORS

1/5-Scale Test

Shock	Accel. (g)	Displ. R _{ref} (in.)	Test 4 (in.)	Test 1 (in.)	Test 6 (in.)	Test 8 (in.)	R _{vis} (in.)	S	$\frac{R_{ref}-\bar{R}_{vis}}{R_{ref}}$
3	0.5	1.51	1.57	1.51	1.55	1.59	1.56	0.019	0.033
9	0.5	1.39	1.42	1.43	1.44	1.45	1.435	0.008	0.032

1/2-Scale Test

Shock	Accel. (g)	Displ. R _{ref} (in.)	Test 33 (in.)	Test 26 (in.)	Test 34 (in.)	Test 11 (in.)	R _{vis} (in.)	S	$\frac{P_{ref}-\bar{R}_{vis}}{R_{ref}}$
3	0.71	5.31	5.67	5.65	5.67	5.80	5.67	0.020	0.07
9	0.71	4.92	5.27	5.28	5.31	5.40	5.19	0.027	0.05

Fractional standard deviation,

$$\hat{S} = \frac{\left[\frac{1}{N} \sum_{n=1}^N (R - \bar{R}_{vis})^2 \right]^{1/2}}{\bar{R}_{vis}}$$

unconstrained in all six degrees of freedom. It could mean the difference between an element hitting another element slightly on an edge instead of perfectly flat, which will make a large difference in the recorded load magnitude. If it is assumed that the waveform deviations in the sinusoidal dwell adequately represent these errors, repeated load recordings from each cycle in the dwell can be used to calculate these errors. This is shown in Table 7-2, which gives typical dwell data from the 1/5- and 1/2-scale tests. For the 1/5-scale instruments, a standard deviation (1σ) of 16% was obtained for the boundary support instrument and 14% for the in-core strain gage measuring impact load. The 1/2-scale boundary support instrument showed a 12% error. No attempt was made here to estimate the 1/2-scale in-core strain gage error.

These errors are exclusive of the effects of test rig configuration and initial condition errors as well as core element property errors since the conditions under which the sweep data was obtained kept these parameters constant. The values include some data acquisition errors and extraneous errors, but these are small in comparison and can be ignored.

The errors in the element displacement and velocity response could not be calculated this way since no Visicorder data were available. However, these errors are likely to be considerably smaller since they are lower order quantities. By performing arbitrary estimates, the errors in the velocity and displacement responses were determined to be 2/3 and 1/2 of that for the force, respectively.

Also, the effect on the core resonant frequency could not be estimated for the same reason. From full-array test data (Ref. 4), however, the change in resonant frequency with g-level is approximately 3.0 Hz/g. Assuming this to apply to the two-dimensional test array as well, the error in the 1/5- and 1/2-scale resonant frequencies would become:

$$1/5 \text{ scale: } 0.5 \times 0.014 \times 3.0 = 2.1\% \quad ,$$

$$1/2 \text{ scale: } 0.71 \times 0.024 \times 3.0 = 5.0\% \quad .$$

TABLE 7-2
ONE-FIFTH AND ONE-HALF SCALE MAGNITUDE AND WAVEFORM ERRORS IN THE RESPONSE

1/5-Scale Test 0.2 in. Gap, 9 Hz		1/2-Scale Test 0.5 in. Gap, 5.2 Hz
LC-072 (1b)	CS-65T (1b)	LC-072 (1b)
181	178	2340
242	212	2340
204	150	2150
188	178	2120
242	256	2120
204	216	2460
181	178	2825
174	198	2210
188	208	2040
188	220	2430
143	220	2850
143	178	1870

$$\bar{u} = \frac{\sum u}{n}$$

$$\hat{S} = \sqrt{\frac{\frac{1}{n} \sum (u - \bar{u})^2}{\bar{u}}}$$

190 lb

199 lb

2313 lb

16%

14%

12%

The accuracy of the test rig frequency input was obtained by checking the dc proportional to frequency channel. This was done by comparing the test rig LVDT displacement data period to the specified period for a sine dwell test. From the 1/5-scale tests, a small error of -1.2% was obtained. The random error in the frequency measurements was also estimated, measuring the spread of signal noise in a sine sweep (Fig. 7-1). It is seen that the maximum error (3σ) is only about 1%.

7.1.2. Test Rig Configuration and Initial Conditions

Test rig configuration errors arose from core element dimensional tolerances, element vertical support location tolerances, and side support adjustment tolerances. However, from one test to another the vertical support locations were kept constant, and only one element in a core array was displaced. The tolerance across the flats of an element was ± 0.005 in. 1/5-scale and ± 0.010 in. 1/2-scale. The side support adjustment tolerances were ± 0.005 in. and ± 0.010 in., respectively. Hence, the maximum variation in gap in a core array was:

$$1/5 \text{ scale: } \pm \sqrt{(0.005)^2 + 2 (0.005)^2} = \pm 0.009 \text{ in.} ,$$

$$1/2 \text{ scale: } \pm \sqrt{(0.010)^2 + 2 (0.010)^2} = \pm 0.017 \text{ in.} .$$

The sensitivity of the core response from a change in core gap was obtained assuming a linear relationship inside the range of gap values tested. From Figs. 4-22, 5-11, and 7-2 through 7-5:

<u>Parametric Rate of Change</u>	<u>Resonant Frequency (Hz/in.)</u>	<u>Boundary Force (lb/in.)</u>	<u>Element Force (lb/in.)</u>	<u>Element Velocity (in/sec)</u>
1/5 scale	26.7	570	300	18.7
1/2 scale	7.2	4750	—	8.6

Fig. 7-1. Digital frequency random variation

Fig. 7-2. Maximum boundary support force and core velocity vs core gap (1/5-scale test)

Fig. 7-3. Maximum boundary support force and in-core force vs core gap (1/5-scale test)

Fig. 7-4. Maximum boundary support force and core velocity vs core gap (1/2-scale test)

Fig. 7-5. Maximum boundary support force vs core gap (1/2-scale test)

The respective response errors were calculated based on the average response corresponding to mean core gaps of 0.2 in. and 0.5 in. for 1/5 and 1/2 scale, respectively. The error values are shown in Tables 7-3 and 7-4.

The initial conditions, such as the initial fuel element gap configuration, were assumed to have little influence on the maximum response values because of the high damping in the system, which will quickly eliminate any starting transients. This may not be true, however, if the maximum response is generated in the very early part of the earthquake time history. As it turned out, the maximum response occurred late in the earthquake.

7.1.3. Core Element Properties

Changes in element properties that can affect the core response are deviations in graphite density (block weight), Young's modulus (block stiffness), and coefficient of friction. The random error in the response as a result of expected deviations in these quantities has not been derived experimentally. The error assessment has therefore been made on a theoretical basis. From code sensitivity studies (Ref. 21) the effects of element density and friction changes are small in comparison with a change in Young's modulus. The mean element modulus for H-451 graphite in the radial direction has been experimentally determined as $E = 1.07 \times 10^6$ lb/in.² with a standard deviation (1σ) of 0.06×10^6 lb/in.². The modulus only affects the core element and core support forces since displacement and velocity are virtually independent of stiffness. Thus, assuming $F \propto \sqrt{K}$, the error in the response becomes 2.8%.

7.1.4. Data Acquisition System

The data acquisition system errors include transducer sensitivity errors and errors in the signal conditioning, filtering, amplification, and recording stages of the system. These component errors are specified by

TABLE 7-3
TOTAL ERRORS IN THE 1/5-SCALE TEST DATA

Test Data	Instrument	Random Error (%) ^(a)						Total
		Rig Control	Rig Config.	El. Properties	Data Acquisition	Inst. Cal.	Extraneous	
Resonant frequency	DC $\propto$ frequency	2.1	2.6	0	0.3	--	0.7	3.4 (1.7) ^(b)
Boundary support force	Load cells	16.0	1.2	2.8	0.8	1.7	0.7	16 (5.6)
Element deflection	Dees gage	7.0	1.6	0	1.6	2.0	0.7	7.7 (3.6)
Element velocity	Dees gage	9.0	1.6	0	1.6	2.6	0.7	9.70
Element impact force	Strain gage	14.0	0.7	2.8	2.4	16.5	0.7	22 (5.1)

(a) All errors represent 1 σ values.

(b) Numbers in brackets were obtained from repeated test data.

TABLE 7-4
TOTAL ERRORS IN THE 1/2-SCALE TEST DATA

Test Data	Instrument	Random Error (%) (a)						Total (RSS)
		Rig Control	Rig Config.	Element Prop.	Data Acquisition	Inst. Calibr.	Extraneous	
Resonant frequency	DC frequency	5.0	1.6	0	0.3	--	0.7	5.3 (2.7)(b)
Boundary support	Load cells	12.0	2.2	2.8	1.8	5.0	0.7	14 (12.9)
force								
Element deflection	Eddy current probe	6.0	0.6	0	0.6	1.7	0.7	6.3 (6.7)
Element velocity	Eddy current probe	8.0	0.6	0	0.6	2.4	0.7	8.4
Element impact	Strain gage	--	--	2.8	2.9	350	0.7	350
force								

(a) All errors represent 1 σ values.

(b) Numbers in brackets were obtained from repeated test data.

the manufacturers and are given in Tables 4-3 and 5-2. They represent 3 σ values. The estimation of the total system error for each instrument is therefore obtained from schematic diagrams such as that for the eddy current probe (Fig. 7-6). The total error in each transducer circuit is given in Tables 7-3 and 7-4 for both 1/5-scale and 1/2-scale test transducers.

7.1.5. Transducer Calibration or Verification

When a strain gage is required to measure strain, the accuracy of the measurement is only dependent on the error in the gage itself and the signal conditioning and recording equipment. However, if the strain gage is required to measure force, additional errors may occur from this special application since calibration or verification is necessary. The instruments that require calibration or verification are (1) strain gages used to measure element impact force, (2) crystal load cells used in a boundary support assembly to measure force, and (3) in-core displacement transducers differentiated to give velocity.

The errors in the strain gage and load cell calibration and verification were assessed from Refs. 6, 9, and 16, and are given in Tables 7-3 and 7-4. It is obvious from the table that the use of strain gages to measure force is not very accurate, in particular in the 1/2-scale test. For this reason, the 1/2-scale core element impact forces have not been reported. The 1/5-scale forces are included but may be subjected to a maximum 50% application error as shown.

The in-core displacement transducers were not calibrated to measure velocity directly. This was handled in the data reduction software. The error in this process was limited to 5% by employing as many as 20 instrumentation channels by multiplexer to measure the in-core displacement. This effectively reduced the digital time step to $0.005/20 = 0.00025$ s. The maximum error in the in-core displacement transducers was estimated typically as 6.0% for the Dees gage and 5.0% for the eddy current probe in the average displacement range of 0 to 0.020 in. (Fig. 7-7).

Fig. 7-6. Error diagram for in-core displacement instrumentation circuit

Fig. 7-7. In-core displacement transducer calibration curve

7.1.6. Extraneous Errors

Extraneous errors were somewhat ambiguous in nature. For example, dc shifts, sometimes seen on the data plots, possibly originated in the bridge amplifier, but they could be due to temperature changes in other components. Also, 60 cycle noise often entered at one or more of the electrical circuits. These errors were generally handled test by test, compensating for the systematic components where observed. Typical random noise levels from test data were about 1% to 2%.

7.2. TOTAL ERRORS

The total random errors in the measured data are given in Tables 7-3 and 7-4 for the 1/5- and 1/2-scale tests, respectively. These represent the compounded sum of the errors by the RSS method,

$$e_T = \left[\sum_{i=1}^N e_i^2 \right]^{1/2}$$

where e_i is the single test system component error. These errors represent one standard deviation (1σ).

7.3. REPEATABILITY

As mentioned earlier, only a few tests were repeated once and the random errors in the data could therefore not be obtained in a meaningful way from statistical analysis. However, by plotting the response as a function of the eight core gap values tested, an evaluation of the spread in the data can be made resulting in an error estimate with respect to a mean curve fit. The error is therefore represented by the fractional standard deviation:

$$\hat{s} = \frac{\left[\frac{1}{n} \sum_{n=1}^N (u_a - u_m) \right]^{1/2}}{\bar{u}_m}$$

where $(u_a - u_m)$ = deviation of the data point from the mean curve fit,
 $\bar{u}_m$ = mean value of all data points.

Such estimates were made for the maximum boundary support force, in-core element force, and core velocity for both 1/5- and 1/2-scale sine sweep tests as shown in Figs. 7-2 through 7-5. An identical analysis was made to obtain the error in the 1/5- and 1/2-scale resonant frequencies. This analysis was based on the data represented in Figs. 4-22 and 5-11.

The results are shown in brackets in Tables 7-3 and 7-4. It is seen that these statistical calculations yield errors that are smaller than those obtained by compounding the component errors. This shows that the method of compounding produces reasonable if not conservative error estimates.

8. REFERENCES

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